TRIAXIAL TESTING OF BITUMINOUS MIXTURES

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PURDUE UNIVERSITY
LAFAYETTE INDIANA

by

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Technical Paper

TRIAXIAL TESTING OF BITUMINOUS MIXTURES

TO: K. B. Woods, Director
Joint Highway Research Project

March 25, 1959

FROM: H. L. Michael, Assistant Director
Joint Highway Research Project

File: 2-4
Project: C-36-6

Attached is a technical paper entitled, "Triaxial Testing of Bituminous Mixtures," by W. H. Goetz and J. H. Schaub, members of our staff.

The paper was prepared for presentation to the American Society for Testing Materials. It is a summarization of information on triaxial testing, much of which has been developed at Purdue in our laboratories. The report is presented for the record.

Respectfully submitted,

H. L. Michael, Secretary

HLM:ac

Attachment

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Technical Paper

Triaxial Testing of Bituminous Mixtures

by

W. H. Goetz, Research Engineer
J. H. Schaub, Research Engineer

Joint Highway Research Project
Project No. C-36-6
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Prepared for Presentation to the
American Society for Testing Materials

Purdue University
Lafayette, Indiana
March 25, 1959

TRIAXIAL TESTING OF BITUMINOUS MIXTURES

For approximately twenty-five years the attention of paving design engineers has been directed in part toward the use of a triaxial shear strength method of test to evaluate the properties of bituminous mixtures. Interest in this form of test, particularly as a means of evaluating fundamental strength properties of bituminous mixtures, has become increasingly greater. At the present time there are several techniques in use that utilize the principles of triaxial shear testing for the design and strength evaluation of bituminous concrete mixtures. The purpose of this paper is to summarize the status of triaxial testing as a mix design and research tool and to present a resume of the various triaxial test procedures that are in use.

THEORY OF TRIAXIAL TESTING

The use of the triaxial method of shear-strength testing has been exploited by the field of soil mechanics. As used by soils engineers, the test evaluates the shearing resistance of plastic or semi-plastic materials under various conditions of simultaneous axial and lateral loading. As pointed out by numerous authors there is an analogy between soil - composed of soil solids, water and sometimes air - and a bituminous - aggregate mixture - composed of aggregate, bitumen and air. It was a logical step to apply the theories developed for soils to the similar plastic mixture of asphalt and aggregate.

Early attempts to utilize triaxial relationships to evaluate bituminous paving mixtures were reported by Hveem (15), Nijboer (11, 12), Endersby (3, 4) and Smith (13, 14). The present day methods of test are due largely to the work of these and other researchers.

In general, the theory of triaxial testing is relatively simple. A triaxial test may be described as a compression test performed with the test specimen supported by a confining pressure. If tests are performed at two or more different confining pressures, an analysis of the relationship between the axial and lateral loads may be used to evaluate the shear strength of the specimen. In most cases, this analysis is performed by the methods developed by Otto Mohr (10) and makes use of the familiar Mohr circle of stress and envelope of failure.

The Mohr analysis may be illustrated by Figure 1. It may be seen from the diagram that the envelope of failure is a graphical representation of the Coulomb Equation, $s = c + p \tan \phi$, where

s = shear strength (psi)

c = cohesion (psi) (the value of s when the normal stress is zero - see Figure 1)

p = normal stress (psi) in the plane of failure

ϕ = angle of internal friction (slope of the envelope of failure - see Figure 1)

In order for the theoretical stress analysis to be valid, shear planes must be free to develop within the sample without restraint. A specimen that is short relative to its diameter will have confining stresses induced at the ends of the sample by the loading heads that will tend to restrict the development of the shear planes and act as a type of sample confinement. The sample must be sufficiently long to permit the shear planes to form within that portion of the samples that is free of end restraint effects. The necessary length will be a function of the sample diameter and the angle of the shear plane with the horizontal (See Figure 1). In general, a sample with a

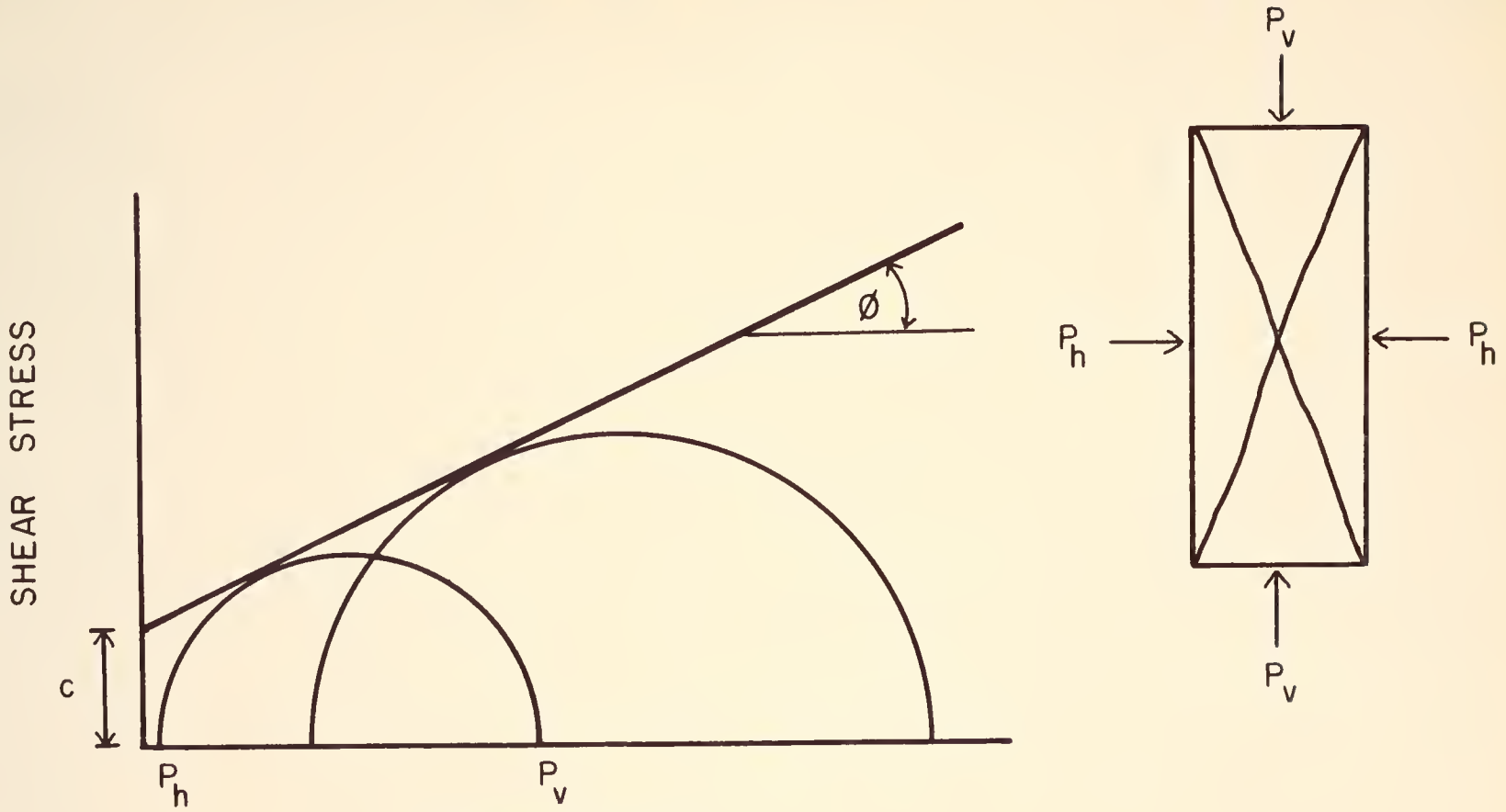

Fig. 1 Triaxial Stress System and Envelope of Failure

length to diameter (L/D) ratio of two or three to one will satisfy this criterion. Samples with L/D ratios of this magnitude are frequently spoken of as "rational samples". Larger L/D ratios are not satisfactory because of the column action that can develop. It should be noted, however, that certain of the triaxial tests utilize a sample that is not rational by the above defination. The Hveem Stabilometer, for example, uses a specimen that is 4 in. in diameter by 2.5 in. in height. Such tests, though triaxial in nature, are not subject to the theroetical stress analysis. It may be argued that samples with L/D ratios of less than two are more nearly comparable to the pavement surface prototype.

On the basis of the Mohr Theory, it would appear that the evaluation of the minimum shearing resistance offered by a specimen is a fairly simple and straight-forward matter. However, it has been shown by soil mechanics research that:

(1) shear strength is a function of the void ratio of the specimen.

(2) the values of the cohesion ("c") and the angle of internal friction ("Ø") are variables whose values depend upon the details of the method of test. It should be clearly understood that the shear-strength parameters "c" and "Ø" are not fundamental properties of a material but are merely convenient terms for the discussion of the shear strength of the material.

Constant Lateral Pressure Tests

A triaxial test may be performed under conditions where the lateral or confining pressure is maintained constant, or under conditions where the lateral pressure is allowed to increase as the test progresses.

The laboratory procedure for the performance of a triaxial test by the constant lateral pressure procedure may be illustrated by Figure 2.

The sample, formed by one of the various compaction schemes, is placed between the loading heads of the triaxial cell and sealed into place by means of an impervious rubber membrane that surrounds the sample and is fastened to the heads. The space between the sample and the walls of the cell is filled with a fluid (castor oil, glycerin, water, or a gas such as air) to which a lateral pressure may be applied and thus transferred to the sample. Axial load is applied through a piston activated by a press or other loading device. The schematic diagram shown the introduction of a proving ring between the piston and the sample to provide an accurate measure of applied axial load. By using the proving ring in this position, friction between the piston and its bearing are eliminated from consideration. Vertical deformations are measured by an extensometer. Note that the drainage connections to the sample heads may be left open or closed during the test. In the case of the usual bituminous mixture, the drainage is the flow of air from the specimen under a head resulting from the lateral pressure applied to specimen.

At this point one of the variables in test procedure becomes apparent. Recall that the equation, $s = c + p \tan \phi$, is used to define shear strength and that in this equation the term p is the effective normal stress acting on the plane of failure. If any pressure is built up within the sample, this pressure acts against the applied load to reduce the effective normal pressure and thus the measured shearing resistance. On this basis, it seems quite likely that the drainage conditions permitted during the test will greatly influence the results obtained from a particular test. In soil mechanics, where saturated

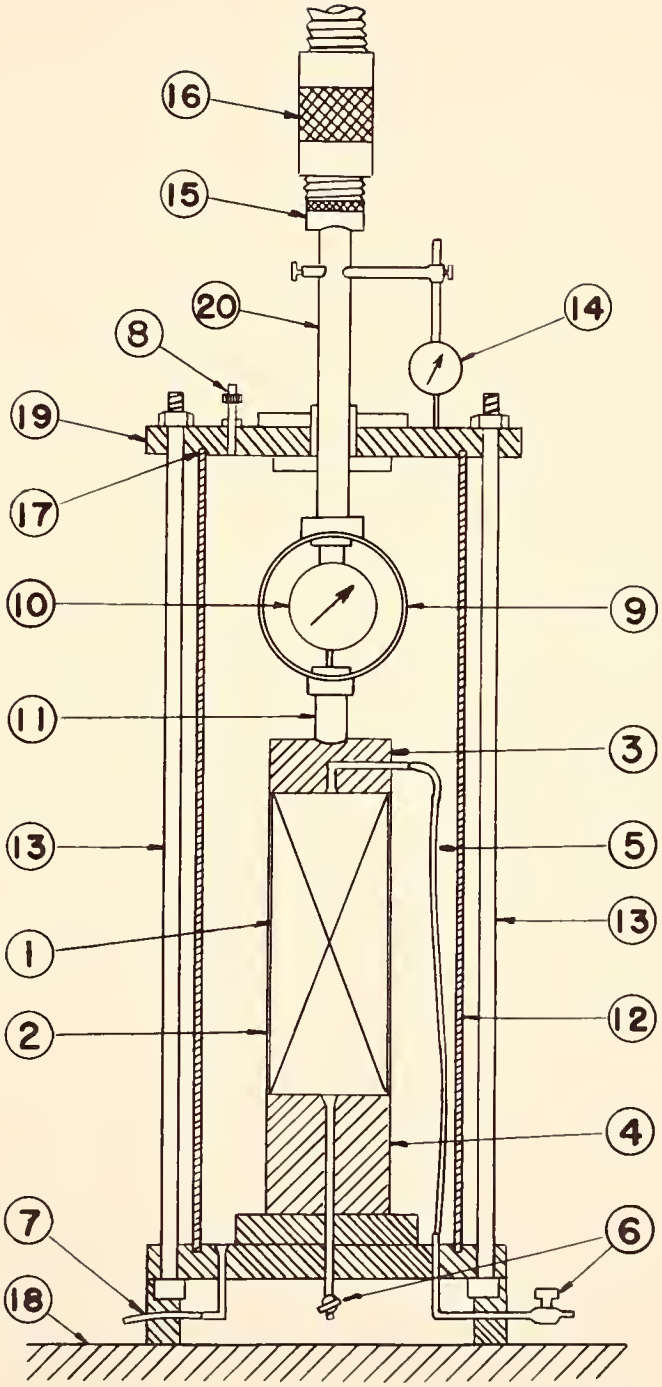

Fig. 2 Diagramatic Sketch of Triaxial Cell

Constant Lateral Pressure

Key to Figure 2

1. Rubber membrane
2. Test specimen
3. Upper loading head
4. Bottom loading head
5. Flexible drainage connection
6. Bottom drainage connection
7. Cell liquid inlet
8. Pressure relief valve
9. Proving ring
10. Load dial indicator
11. Loading piston
12. Cell wall
13. Threaded connecting rod
14. Vertical-movement dial indicator
15. Adapter between turnbuckle and loading piston
16. Turnbuckle for applying seating load
17. Rubber gasket
18. Lower platen of testing machine
19. Cover plate

soils are tested in most cases and the drainage is composed of water squeezed from the sample voids during the test, the various combinations of drained and undrained conditions (including the effect of rate of loading) form the basisfor the classification of triaxial test types. There has been no such refinement applied to the triaxial testing of bituminous mixtures.

An interesting variation of the constant lateral pressure triaxial procedure is the vacuum triaxial technique. In this method of conducting the test, lateral pressures are supplied by applying a vacuum to the inside of the specimen. The applied lateral pressure is the difference between the internal and external pressurers acting on the sample. Obviously, the maximum value of the lateral pressure that may be applied by this method is limited to atmospheric pressure. The details of the vacuum triaxial technique, as applied to the testing of bituminous mixtures, have been presented by Goetz and Chen (5).

A special case of the constant lateral pressure triaxial test is the unconfined compression test. This test may be considered as a triaxial test with a confining pressure equal to zero. In other words, the stress difference at failure is equal to the axial pressure applied to the sample. Compression tests such as the ASTM Compression Test (D1074-58T) are sometimes referred to as unconfined, but unless they utilize a specimen tall enough to meet the criterion for rationality as previously described, they are not unconfined tests.

Variable Lateral Pressure Tests

To this point the discussion has been confined to what might be called a conventional triaxial test; ie, the lateral pressure is held

constant while the axial pressure is increased to a failure condition. Several of the triaxial test methods make use of a variation of this procedure and permit the lateral pressure to vary as a result of the applied vertical pressure. It is this procedure that forms the basis of the work of Hveem (15), Nijboer (11, 12) and Smith (13, 14). It has become customary to speak of this form of the triaxial test as a "closed system" test while the method previously discussed is known as the "open system". It is the authors' preference to speak of these tests as variable lateral pressure and constant lateral pressure respectively. A schematic diagram of the variable lateral pressure test cell is shown in Figure 3 (14). The basis for the analysis of the variable lateral pressure test is shown by Figure 4 (1).

One of the primary advantages of the variable pressure scheme is illustrated by the computational procedure shown in Figure 4. A single sample is sufficient to measure values of the parameters "c" and "ϕ". In the performance of the test, the sample is placed into a rubber membrane that is a permanent part of the cell. The space between the cell walls and the membrane is completely filled with a liquid. A slight seating load is applied to the sample, followed by increments of axial load with each increment maintained until the rate of deformation becomes negligible. As there is no way for the liquid surrounding the sample to escape, there is a buildup of pressure in the confining liquid that reflects the support required to maintain equilibrium under axial load. Readings of the axial pressure and the developed lateral pressure are then plotted as indicated in Figure 4. The values of "c" and "ϕ" may then be computed.

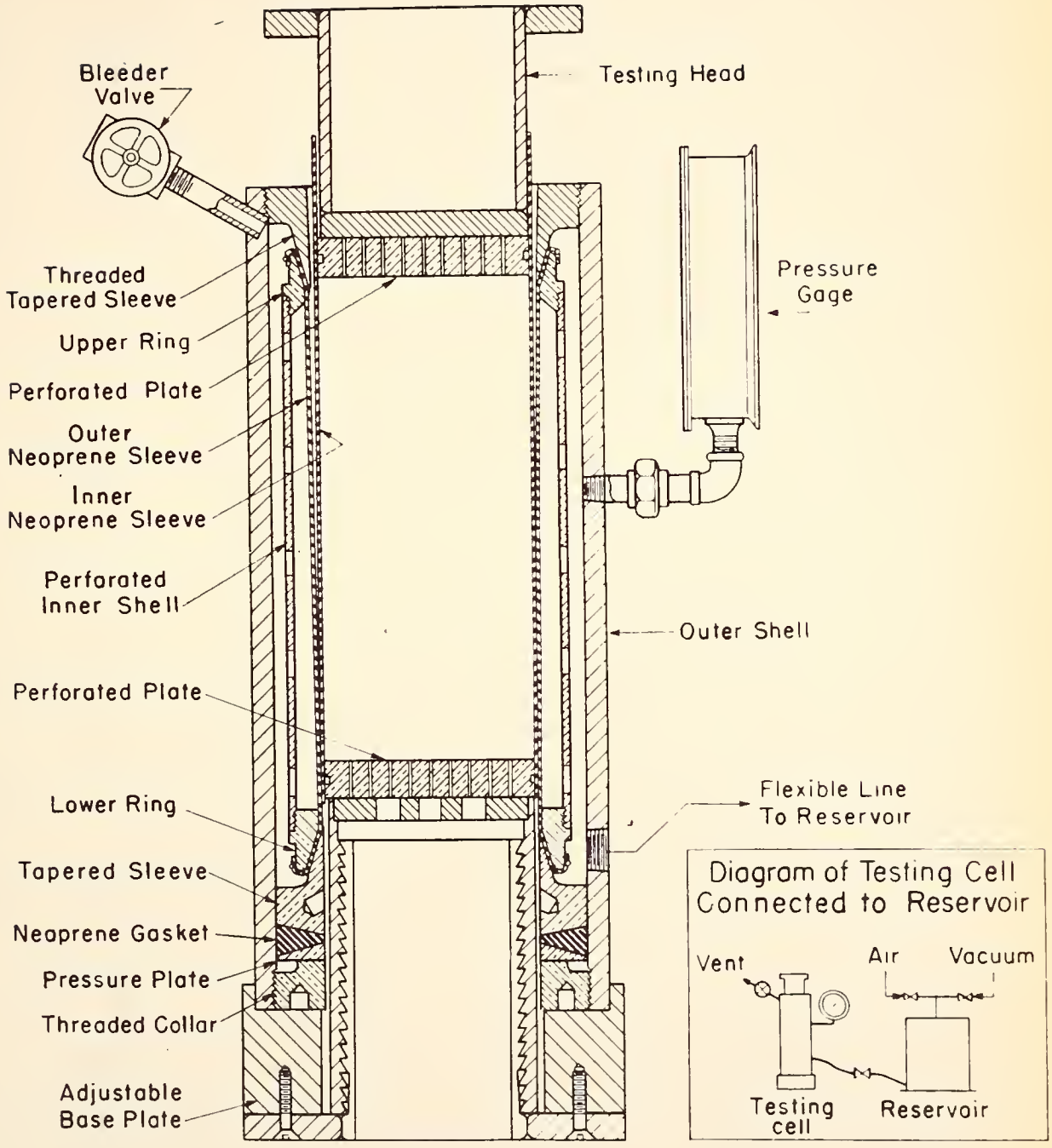

Fig.3 Diagramatic Sketch of Triaxial Cell

Variable Lateral Pressure (after Smith) (14)

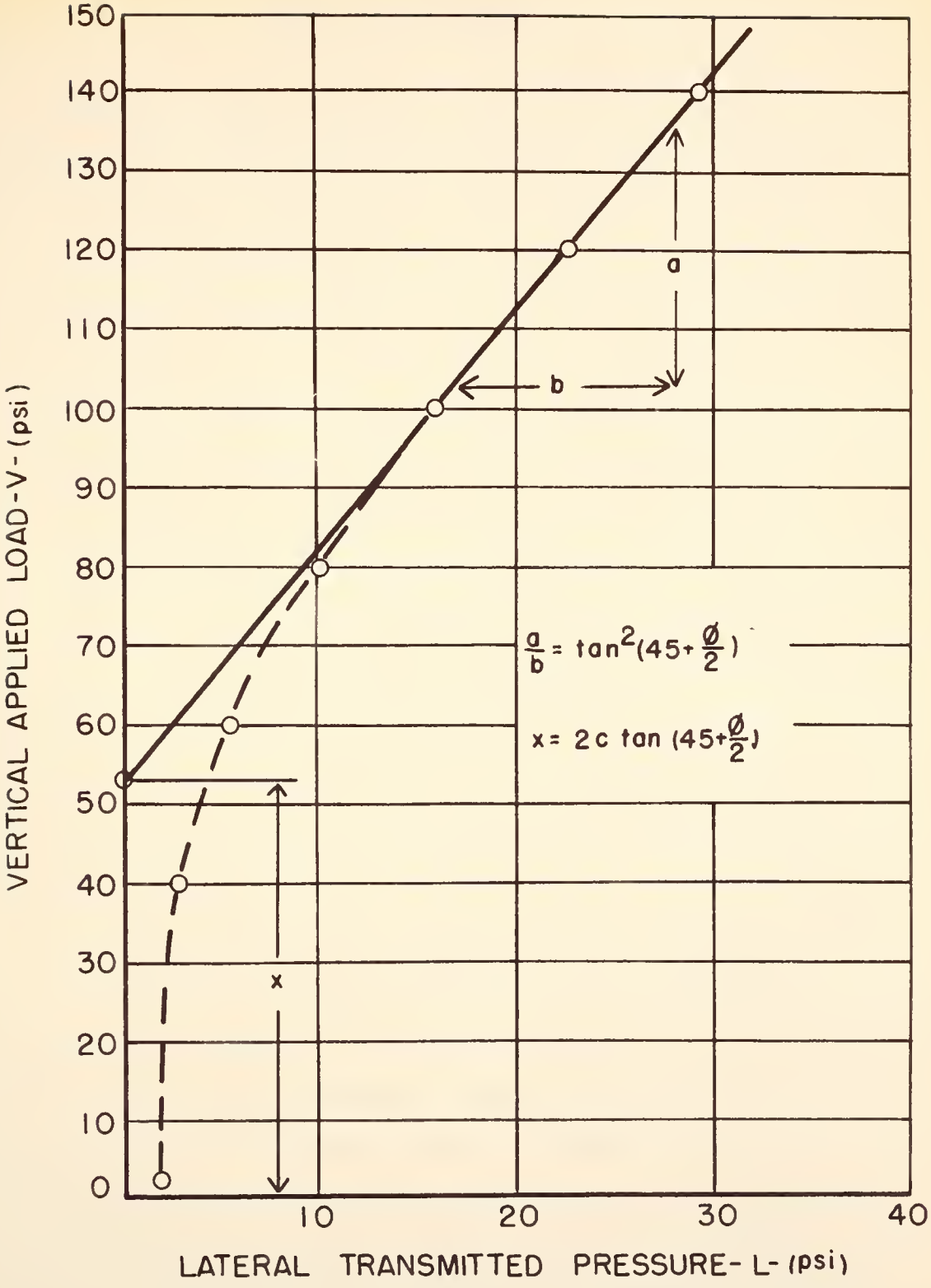

Fig. 4 Typical Results – Variable Lateral Pressure Test (after Asphalt Institute) (1)

USES AND LIMITATIONS

There are numerous advantages inherent with the triaxial test method for the strength testing of bituminous mixtures regardless of which of the various forms are used. In comparison to other methods of test, this scheme approaches the design problem by attempting to evaluate fundamental strength properties of the mixture under specified loading conditions. The stress system that acts upon a sample during the triaxial test approaches the system of stresses that are present during the loading of a mixture when it acts as a part of a pavement structure. Furthermore, the triaxial test makes use of a strength theory that agrees closely with experimental results.

Though it is felt by the authors that the triaxial method of test offers the greatest potential for a rational method of mix design, this should not be construed to mean that the method is without disadvantages. Some of the chief objections to the use of the method arise from the cost and relative complexity of the necessary equipment. In addition, the size of specimens required for the rational testing of coarse-aggregate mixtures and the number of specimens needed for a test series are considered by some as discouraging to the adoption of the method for routine testing. Other disadvantages are to be found in the lack of knowledge of the mechanism of failure and of the load-carrying ability of plastic, three-phase systems. The analysis of triaxial data for bituminous mixtures is often complicated by a curved envelope of failure for which there is no well-defined or proven explanation. In addition, although the triaxial compression test may be performed in a strictly rational (known conditions of stress) manner, lack of

knowledge concerning stress conditions in a pavement layer limits the application of triaxial data to empirical procedures.

Test Variables

There are numerous test variables present in any triaxial test. Some have been mentioned previously, such as; the three-phase system existing in most specimens, the possible effect of drainage conditions on the evaluation of shear strength, and the question of constant vs. variable lateral pressure. Other variables that have been shown to exert an influence of some magnitude on the test results are; the rate of load application or sample deformation, the rheology of the binder, the relative dimensions of the sample for various maximum size coarse aggregates, the effects of the void content of the mixture, and the temperature at which the test is performed. Investigations are proceeding in an attempt to define the effects of each of these variables. However, to the authors' knowledge, there is no triaxial test procedure presently in use that can evaluate each of these variables in a rational manner.

The effects of two variables, rate of deformation of the test specimen and the temperature of the test, are illustrated by Figure 5 (6) and Figure 6 (7). In the former figure, the variation of the measured value of "c" and "ϕ" is shown for various testing speeds at a constant test temperature. Note that the angle of internal friction is affected but slightly by the change in testing speed but the variation in cohesion is pronounced. Figure 6 introduces the further variable of test temperature and indicates the effects of the variables on the observed maximum compressive stress at a constant lateral pressure. As

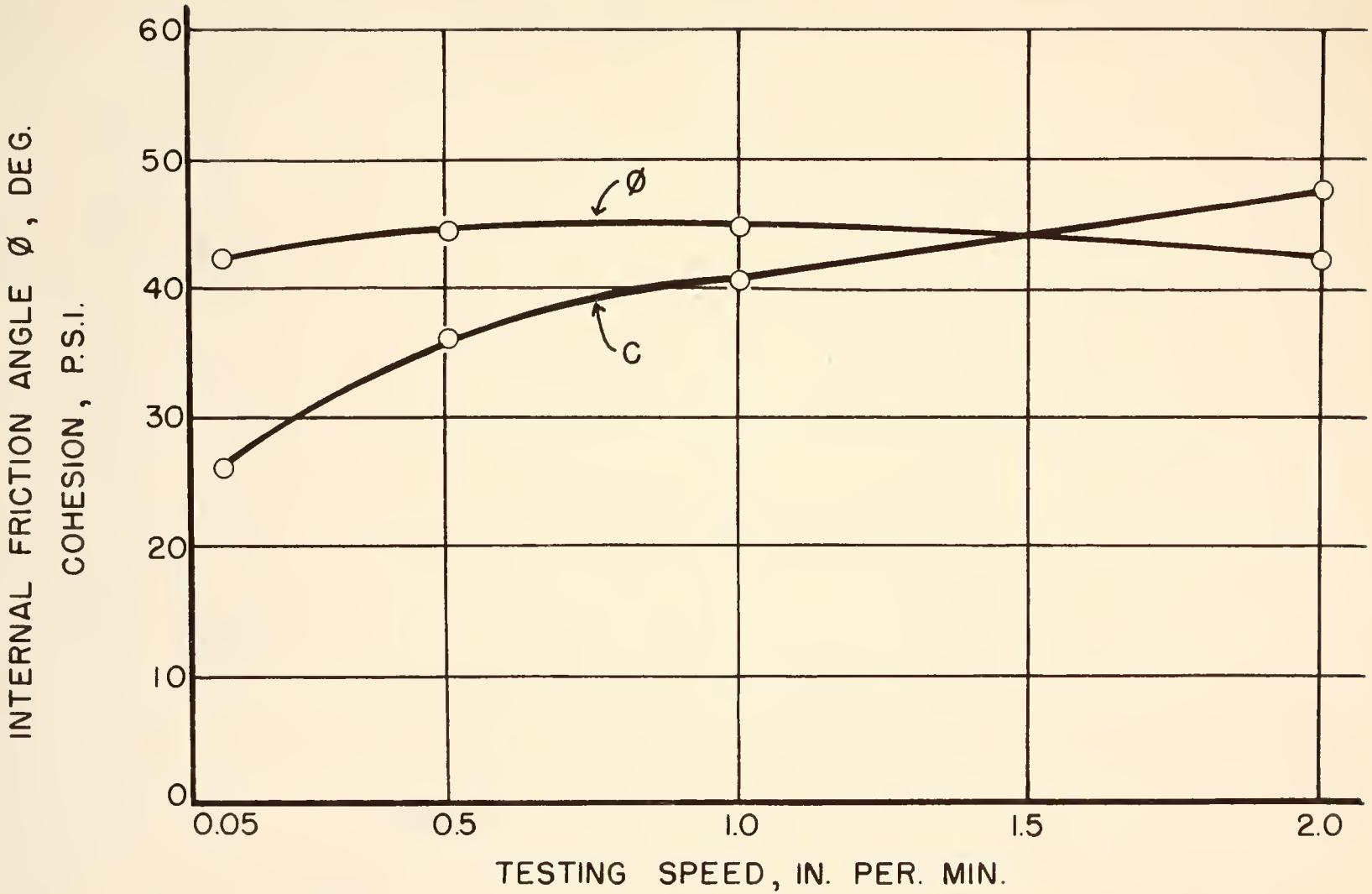

Fig. 5 Variation of C and Ø with Testing Speed (after Goetz) (1)

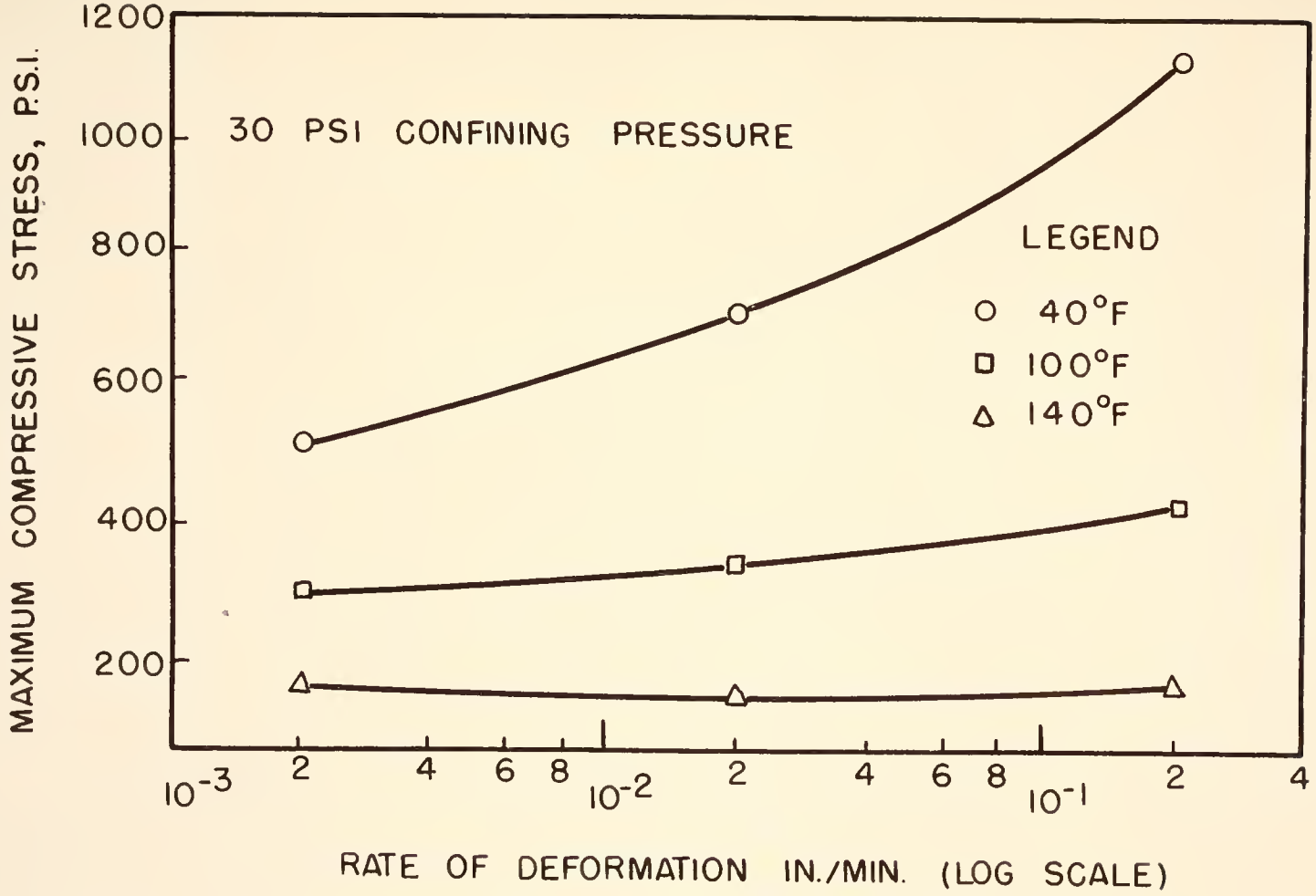

Fig. 6 Variation of Compressive Strength with Testing Speed

(after Goetz, Mc Laughlin, and Wood) (7)

might be expected, strength values decrease with an increase of test temperature. It is interesting to note however, that rate of deformation has less effect on tests performed at high temperature than on tests at low temperature. Of course, viscosity effects of the binder are related to both testing speed and test temperature.

Design Use

Several variations of the triaxial test are presently in use for the design and evaluation of bituminous mixtures. The application of the method to design is limited at present to the more empirical but simpler tests, such as the Hveem Stabilometer. As a research tool, however, the rational triaxial test is in widespread use. From the previous discussion and from the reports of such well known researchers as McLeod (9), Smith (13, 14), Nijboer (11, 12) and others, it appears that the triaxial test offers advantages not matched by other design methods for the investigation of fundamental mix properties.

CONSTANT LATERAL PRESSURE TEST PROCEDURES

The use of the constant lateral pressure test procedure for design purposes is represented by the procedures of the Kansas Highway Department as outlined by Worley (16). By the Kansas procedure, a sample 12 in. high and 5 in. in diameter is molded by a combination of rodding and static compaction. Testing is performed at a temperature of 140 F and at a rate of deformation of 0.01 in. per min. A minimum of two tests at different lateral pressures are used to develop the envelope of failure and thus define values of "c" and "ϕ".

Use in Research

The utilization of the constant lateral pressure triaxial test as a research tool may be illustrated by the continuing investigations being conducted at Purdue University. The cell that is used is illustrated by Figure 2. Typically the test specimens are 10 in. high and 4 in. in diameter, are tested at 77 F, and air pressure is used to provide the lateral pressure. The upper drainage connection is not used and the lower drainage connection is left open to the atmosphere. Various rates of deformation have been utilized in an effort to define the effect of this variable on the measured strength properties. See Figures 5 and 6. In general, an increase in the rate of deformation increases the observed shear strength of a mixture, but the effect appears to decrease with increased test temperatures. Smaller samples and a correspondingly smaller cell have been used for investigating the properties of fine-aggregate mixtures and to study the inter-relationship of strength, test temperature and the rate of deformation. The analysis of the test data is accomplished by the method illustrated by Figure 1.

Figures 7 (6), 8 (6), and 9 (8) are illustrative of the versatility of the triaxial test procedure as a research tool to investigate numerous variables in bituminous mixture design. Figure 7 shows the variation in the measured "c" and "Ø" values with changes in per cent asphalt cement and the variation in stability with per cent asphalt at confining pressures of 0, 10 and 20 psi. Figure 8 illustrates the effect of the consistency of the asphalt on the shear-strength parameters of two mixtures. Figure 9 shows the change in compressive

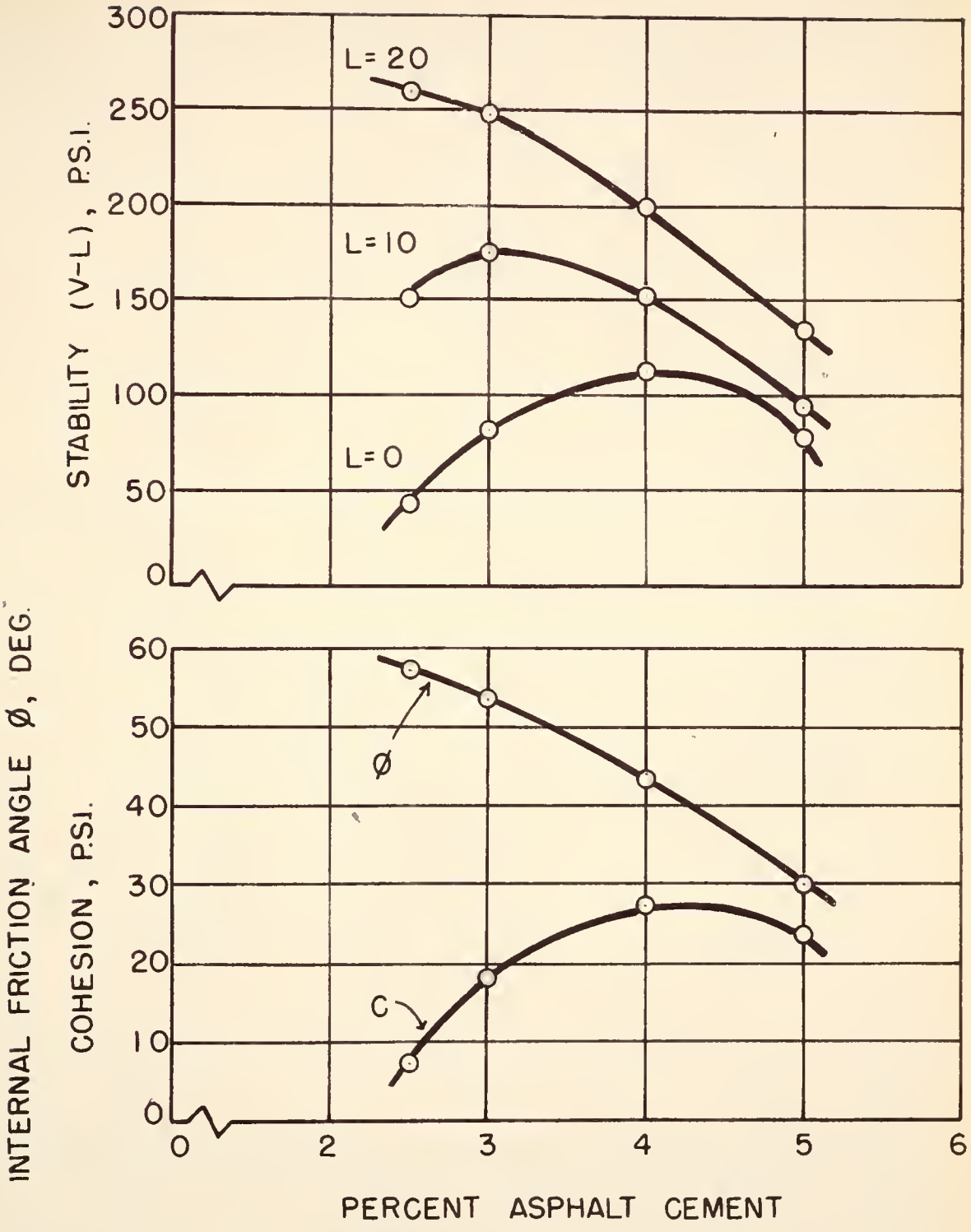

Fig. 7 Variation of Test Properties with Percent Asphalt (after Goetz) (6)

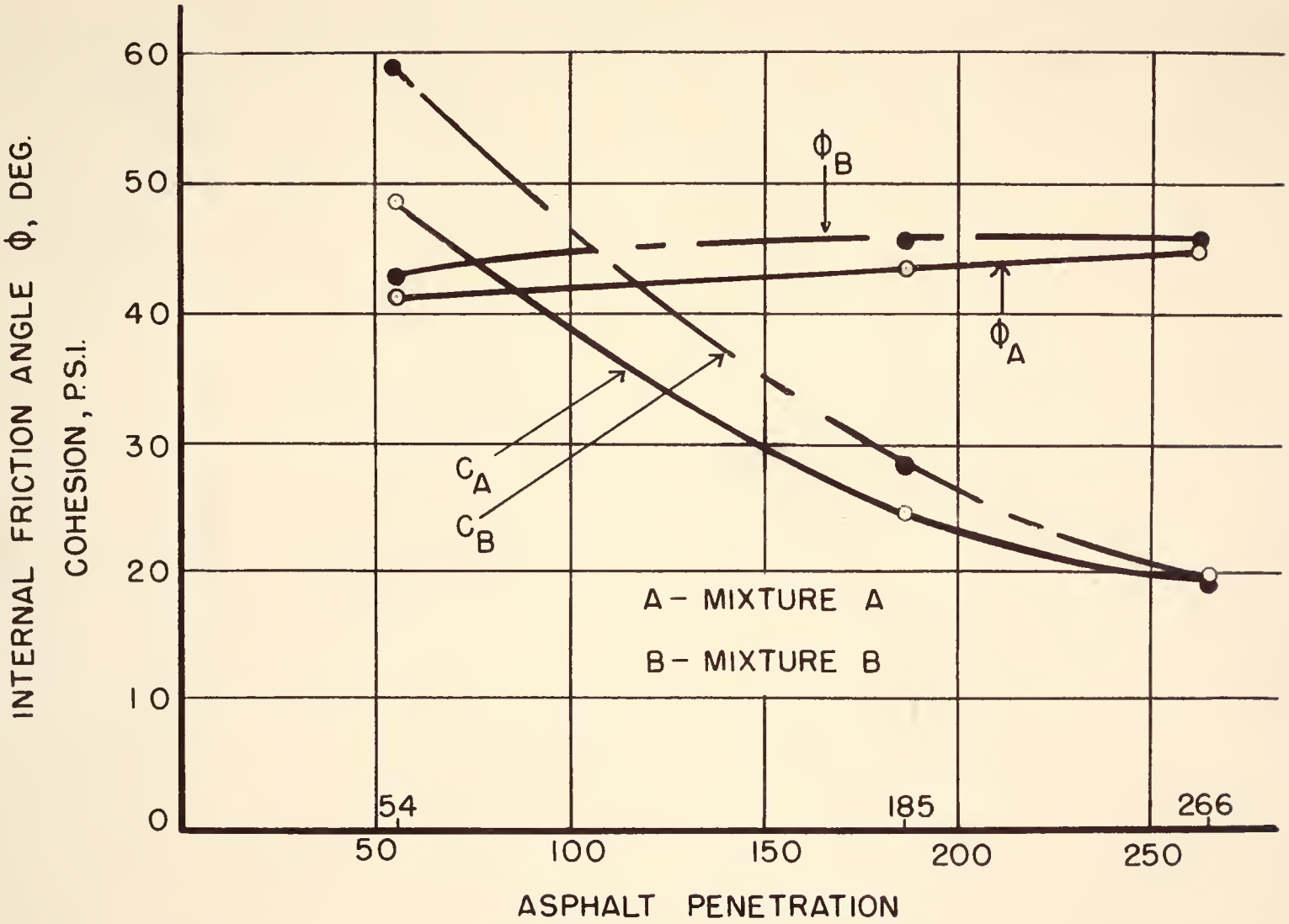

Fig. 8 Variation of C and Φ with Asphalt Grade (after Goetz) (6)

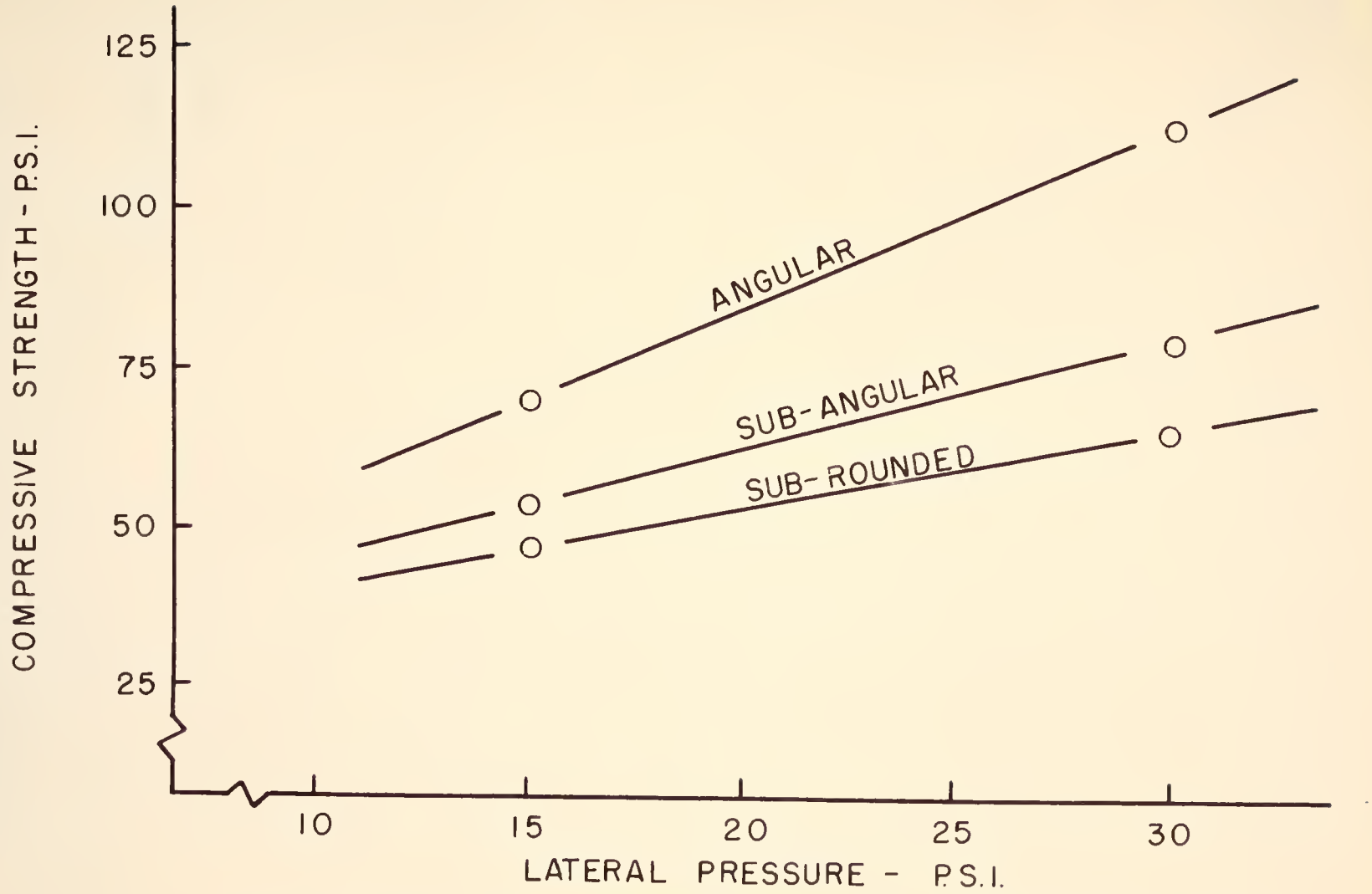

Fig. 9 Effect of Aggregate Shape on Compressive Strength (after Herrin and Goetz) (8)

strength at various lateral pressures that results from changing the shape of a given aggregate. At all lateral pressures indicated the compressive strength becomes greater with an increase in the angularity of the aggregate.

Bureau of Public Roads Cell

An interesting and useful innovation in the constant lateral pressure triaxial cell has been developed by the Bureau of Public Roads. The modified cell makes use of a "free" rubber membrane system and a scheme for introducing the sample into the cell from the bottom that eliminates the need for dismantling the cell between tests. Carpenter, et al (2) describe the "free" rubber membrane system as follows: "In the free-sleeve type, the upper end of the rubber sleeve is attached not to the top plate of the cell but to an upper bearing plate which was designed to operate entirely within the pressurized zone, thus eliminating the longitudinal stretching of the sleeve and indeterminate vertical force component that the stretching entailed ". Temperature control during the test is provided by the use of heated water as a pressure transmission fluid for lateral pressure. The cell is designed for 4 in. diameter specimens and may be used with specimens of various heights with 4 in. and 8 in. being the most commonly used. The samples are deformed at a rate of 0.05 in. per min. per in. of specimen height. A diagram of the Bureau of Public Roads Cell is shown in Figure 10 (2).

Unconfined Compression Test Procedures

The simplest form of the triaxial test is the Unconfined Compression Test. The confining pressure is zero because atmospheric

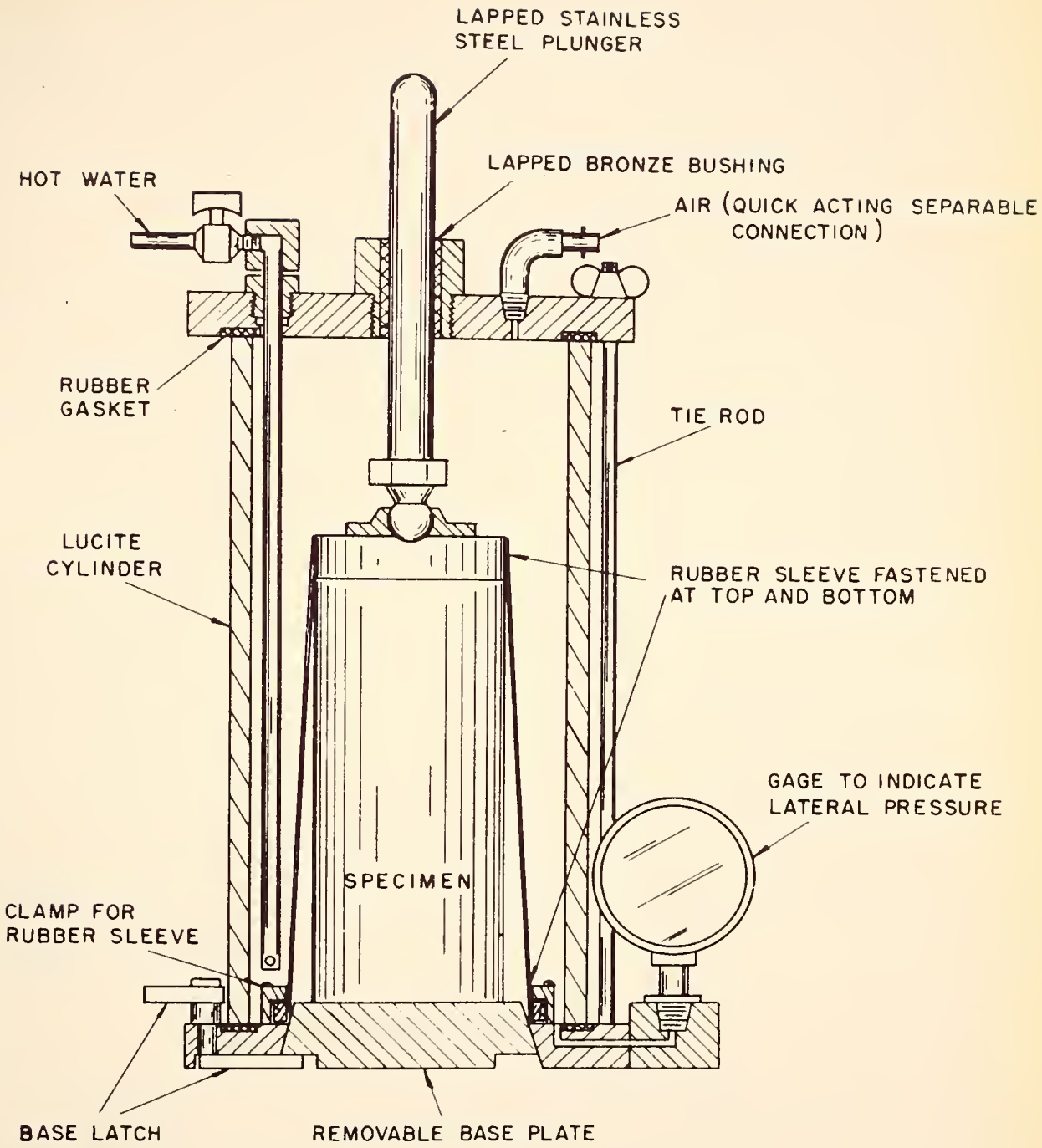

Fig. 10 Diagramatic Sketch of Bureau of Public Roads Cell

(after Carpenter, Goode and Peck) (2)

pressure is acting on both the outside and inside of the specimens The specimen is failed by the application of axial load. In soil mechanics nomenclature such as test is considered a special case of the undrained or quick test in which no drainage or consolidation is permitted under any of the applied loads. In the undrained test, the envelope of failure is typically a horizontal line indicating a zero angle of internal friction. It may be shown that the shearing resistance of the material us one-half of the load producing failure. In the case of a plastic failure, the failure load may be defined as the load causing a given strain in the specimen.

Because of the nature of the test results, a separation of the shear parameters that are acting to produce the shearing resistance of the unconfined compression sample is not possible and the ultimate compressive strength is reported as the axial load causing failure. As a result, the principal use of the test method is as a comparative test. However, compression tests frequently used for such purposes, such as the well-known immersion-compression test (ASTM D 1075-54), are partially confined as a result of end restraint produced in the short specimens that are used.

VARIABLE LATERAL PRESSURE PROCEDURES

There are two very well known forms of the variable lateral pressure triaxial test in use for the design of mixtures. Both the Smith Method of Design and the Hveem Stabilometer Method utilize a similar triaxial cell arrangement. The major differences in the methods are the size of specimen tested and the compressibility of the fluid in the system. The Smith Triaxial Cell utilizes a specimen that is

3.82 in. in diameter and 8 in. high, while the stabilometer specimen is 4 in. in diameter and 2.5 in. in height. An incompressible fluid is used in the Smith Cell, while a controlled amount of air is introduced into the system of the Hveem method. Other procedural differences exist and will be pointed out in the following discussion of each method.

Smith Method

In the Smith triaxial method of design, a testing temperature of 75 ± 2 F is used and the axial load is applied in increments. The time interval between application of load increments varies, with each increment being maintained until the vertical deformation is less than 0.001 in. per min. The load application procedure tends to decrease the viscous resistance of the binder to a negligible quantity. When each load increment is in equilibrium with the confining liquid pressure, the pressure developed in the confining fluid is recorded as the lateral pressure corresponding to the total axial pressure. The test is continued until sufficient points have been established to plot a curve of P_v vs P_h similar to that shown in Figure (1). Computations are made to evaluate "c" and "ϕ" by the procedure indicated in the same figure. In the utilization of the test data to evaluate the mixture, use is made of a design chart that indicates satisfactory and unsatisfactory combinations of the shear strength parameters. See Figure 11 (1). The portion of the chart devoted to satisfactory mixes was developed by study of those mixtures that had a record of adequate performance. The unsatisfactory portions of the chart may be divided into sub-areas in which either or both of the corresponding values of "c" and "ϕ" are lacking in magnitude.

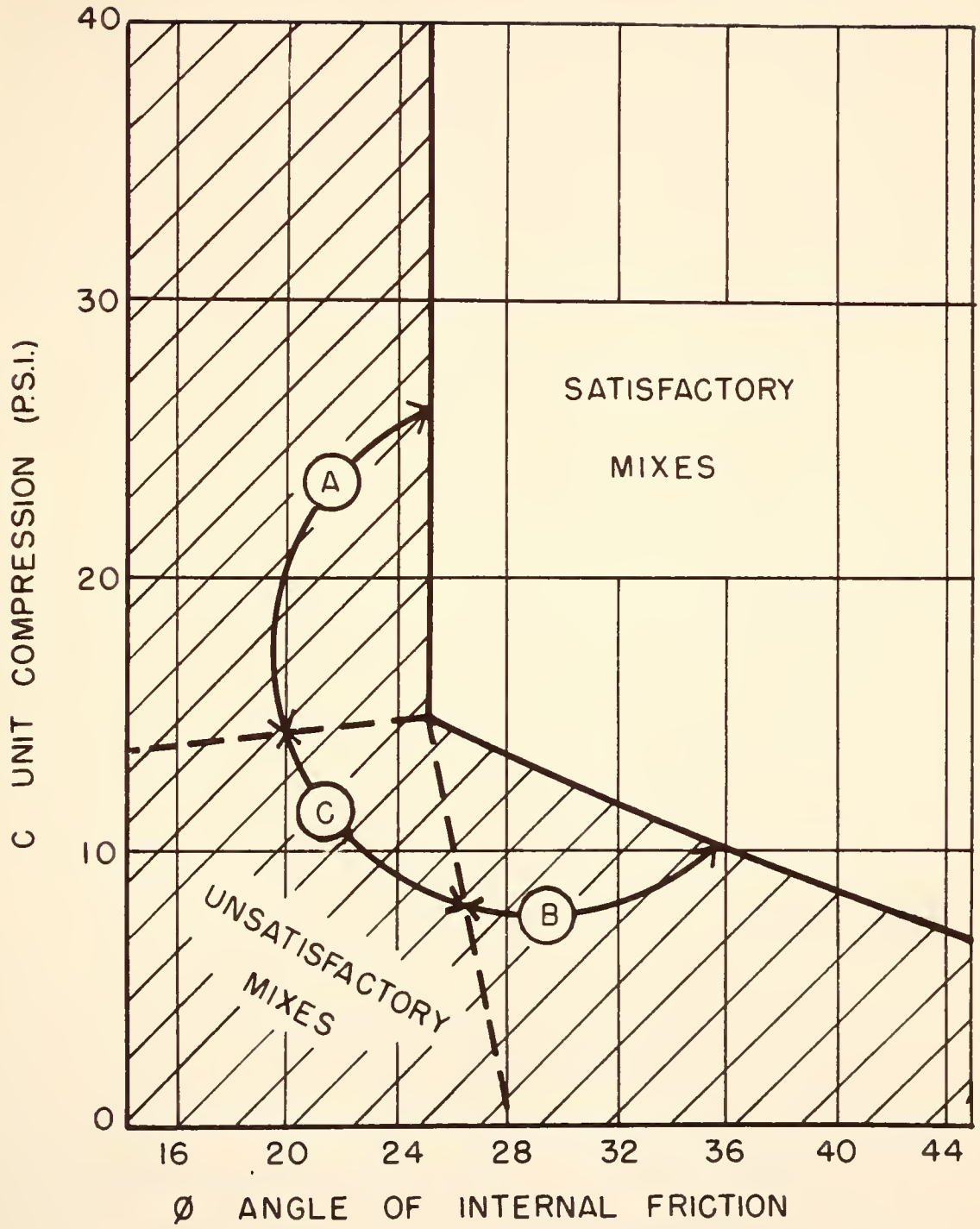

Fig. 11 Triaxial Test Evaluations of Asphaltic Concrete (after Asphalt Institute) (1)

Many advantages are apparent with the Smith method of design. Chief among these is the use of only one sample to define the measured shear strength parameters for a given mixture. Furthermore, the use of static load application subjects the material to the most severe compressive stress conditions that a mixture is required to withstand. The use of static loading reduces the viscous resistance of the binder without resorting to testing at elevated temperatures for this purpose.

At the present time, the Smith triaxial method is used primarily as a research tool.

Hveem Method

Based on the definations established in the preceding discussion, the Hveem Stabilometer test must be considered as a form of triaxial test. The size of the sample used and the effect of the air introduced into the test system make it impossible to analyze the results of this test by theoretical methods. The test is thus triaxial in nature but empirical in analysis.

The Hveem Stabilometer test is conducted on samples previously brought to a temperature of 140 F. The samples are seated in the Stabilometer shown diagramatically in Figure 12 (17) and load is applied axially at a rate of deformation of 0.05 in. per minute to a maximum load of 6000 lb. The lateral pressure developed due to sample deformation under the axial load is noted for various magnitudes of axial load. The relative stability of the test specimen is evaluated from the formula

$$S = \frac{\frac{22.2}{P_h D} + 0.222}{P_v - P_h}$$

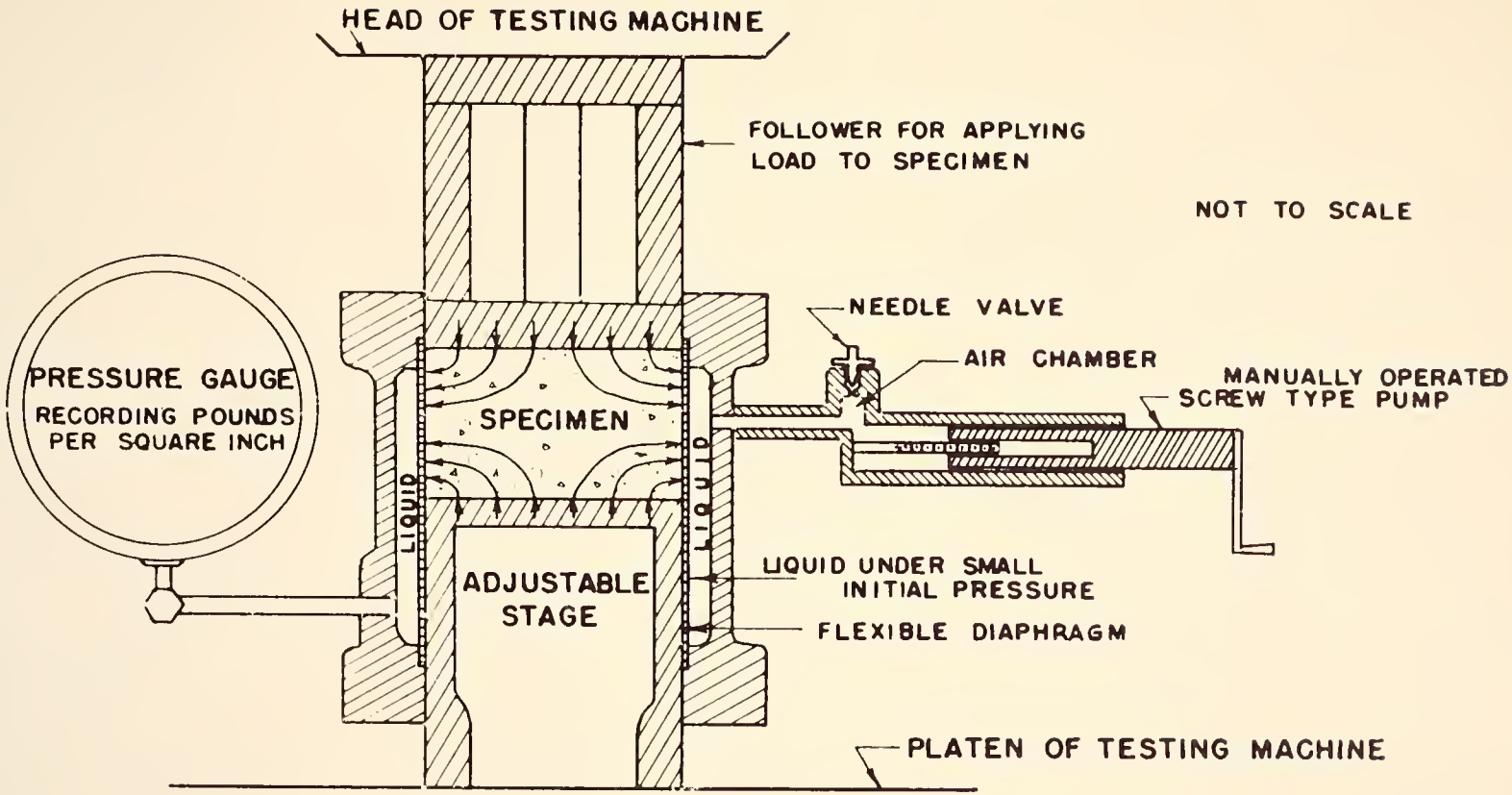

Fig. 12 Diagramatic Sketch of Hveem Stabilometer (after California Division of Highways) (17)

where P_h is the developed lateral pressure of a vertical pressure (P_v) of 400 psi. The D term is the displacement correction applied to compensate for the reduction in lateral pressure due to the presence of air in the system.

It should be noted that the presence of air in the system is an established part of the Stabilometer test. Prior to sample testing, sufficient air is included in the system to require two turns of the displacement pump to change the lateral pressure from 5 psi to 100 psi when using a metal dummy specimen. The displacement term D used in the equation for relative stability corrects for any variation from this fixed amount that occurs when a bituminous mixture specimen is tested.

As the interpretation of the Stabilometer test data is empirical, no attempt is made to serparate the measured strength into components. Cohesion of the mixture is evaluated directly by means of a Cohesiometer test.

Experimentation and experience with mixtures designed by use Hveem method have indicated that it can provide stable mixtures for modern loads.

SUMMARY

The foregoing brief description of the various forms of the triaxial test emphasizes one of the major problems encountered is using the triaxial test for the evaluation of bituminous mixtures. The method is so flexible that there is no acceptable standard of procedure. In fact, there is not even a common nomenclature that is acceptable for the discussion of results. Each of the test procedures mentioned has

merit. Each method has some history of a successful use for the design and evaluation of bituminous mixtures. Unfortunately, however, the very nature of bituminous mixtures has prevented the development of an acceptable and theoretically sound theory of failure that will account for the many variables that must be considered regardless of the particular test method used.

In view of the advantages of the triaxial test method - loading similar to field conditions, statically determinate method of analysis of the results, history of correlation with experience, simplicity of adjustment of given variables, etc, - it seems quite likely that further extensive research will be performed to establish a more firm basis for the use of this method to the design of mixtures. There is a positive need for the separation and evaluation of the test variables as well as for the creation of a procedure that will define the shearing resistance of bituminous mixtures under the varied conditions of pavement loading. Not all of this research may be confined to the laboratory. The proof of any theory of bituminous mixture design lies in the field performance of the mixture designed on the basis of the theory. This, then, indicates a need for extensive correlation studies between laboratory and field performance. In turn, such studies demand closely controlled test activities and long-time observations.

1. Asphalt Institute, Mix Design Methods for Hot-Mix Asphalt Paving, Manual Series No. 2, 1956.

2. C. A. Carpenter, J. F. Goode, and R. A. Peck, "An Improved Triaxial Cell for Testing Bituminous Mixtures Paving Mixtures", Proceedings, The Assoc. of Asphalt Paving Technologists, Vol. 20, 1951.

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